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HYDROPHONE FOR LOW FREQUENCY, LOW LEVEL UNDERWATER SOUND MEASUR--ETC(U)
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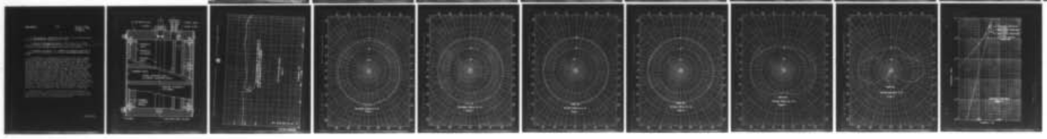

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⑥ HYDROPHONE FOR LOW FREQUENCY, LOW LEVEL UNDERWATER SOUND MEASUREMENTS

⑩ ~~By~~ P. M. Kendig ~~and~~ H. J. Clarke

⑨ Technical memo.

⑭ TM-6.8930-25

Technical Memorandum
File No. TM-6.8930-25
February 2, 1961
Copy No. 15

⑪ 2 Feb 61 ⑫ 22p.

⑮ NOrd-16597

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Reference: (1) P. M. Kendig, J. Acoust. Soc. Am., 33, 674-676 (1961)

Abstract: This memorandum presents the design and performance characteristics of a hydrophone that is intended for low level noise measurements in the frequency range from 100 to 3000 cps. It is constructed of four barium titanate cylinders, each six inch O.D. by two inches long by 0.2 inch thick, that are mounted coaxially and mechanically isolated from each other and the end-plates. The whole unit is enclosed in a water tight boot. The free-field voltage response of the hydrophone is about -78 ±1.5 db re 1 volt per μbar over the specified frequency range and is omnidirectional within ±1 db in both the vertical and horizontal planes over this same frequency range. The equivalent noise pressure of the hydrophone varies from -91 db re 1 μbar for a 1 cps band at 100 cps to -102 db at 3000 cps.

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Introduction and Design Considerations

One limitation to the measurement of low-level, underwater acoustic signals in the ocean is the level of ambient noise of the sea. Therefore, if possible, it is desired to design a hydrophone-amplifier system that can detect this ambient. This memorandum reports on the requirements, design and tests pertaining to the hydrophone of such a system.

A principal requirement of the hydrophone is that it should have a flat response from 100 cps to 3 kc. It should also have no resonance in this range, be essentially omnidirectional, and have an equivalent noise pressure well below 10 db less than the ambient corresponding to zero sea state. This latter level is the value quoted as frequently prevailing in Dabob Bay. The impedance, which is almost entirely capacitive, was specified to be about one megohm at 20 cps.

Since a low equivalent noise pressure is a major requirement, an investigation was made of the hydrophone parameters that determine this quantity (Reference 1). It was shown that, for a cylinder, the square of the equivalent noise pressure varies approximately as the thickness and inversely as the product of the length by the cube of the radius. This indicates that the cylinder should be as large as possible and with a wall as thin as possible. A six-inch diameter cylinder which resonates around 10 kc was considered to be about the maximum feasible size. In order to maintain omnidirectionality to 3 kc, the length should not exceed 8 or 10 inches (about $\lambda/2$). A wall thickness of 0.2 inch was selected because a thinner wall might not withstand the hydrostatic pressure of 300 psi maximum. Other factors to be considered are the loss tangent and the electromechanical coupling coefficient because the square of the equivalent noise pressure also varies approximately as the first power of the former and inversely as the square of the latter. Barium titanate was chosen primarily because it was more readily available in this size. Admittedly, this is not the optimum material, but it will adequately serve for an evaluation of the design and should quite easily meet the specified requirements.

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Design and Construction

The construction of the hydrophone is shown in Figure 1. It consists of four barium titanate cylinders, each six inches O. D. by 2 inches long by 0.2 inch thick, that are mounted coaxially and mechanically isolated from each other and the end-plates. The barium titanate cylinders are mounted on rubber rings which are supported by phenolic cylinders and a phenolic ring between the ends of the cylinders. Since the rubber rings are not completely confined, they should provide effective isolation for the barium titanate cylinders. There are three hollow metal posts on the inside that serve two purposes. They center the phenolic cylinders and support the two metal end plates. The length of these posts are such that the rubber rings are slightly compressed when the bolt on the center post is tightened. The center post is just slightly shorter than the other three so that the end plates rest firmly on the cylinder location posts. Under high hydrostatic pressure, the center post might support the end plates if the pressure were sufficient to bend them. A 3/16-inch hole shown in each of the phenolic cylinders is used to bring the electric leads from the barium titanate cylinders to the inside. Both electrical connections to the barium titanate cylinder can be made on the inside because a plated tab on the inside leads over the edge at one point to the outside of the cylinder. The four cylinders were connected in series in order to increase both the sensitivity and the impedance over the values that would have been obtained for parallel connections. This amounts to 12 db in the sensitivity and a factor of sixteen in the impedance.

After the parts of the hydrophone were all assembled, the unit was enclosed in a tight-fitting rubber boot and sealed at both ends with the boot clamps. This was accomplished by means of a special boot jig in which the rubber boot was inserted in such a manner that both ends of the boot were sealed to provide an airtight space between the outside of the boot and the inside of the boot jig cylinder. An opening to this space was provided so that it could be evacuated, thus expanding the rubber boot enough to slip the hydrophone into the normally undersize boot. A generous quantity of de-gassed castor oil was poured into the space between the hydrophone and the excess castor oil was squeezed out so that the rubber boot made intimate contact with the ceramic cylinders. Finally, the ends of the rubber boot were sealed with boot clamps.

Tests and Measurements

The hydrophone was calibrated at the Black Moshannon Calibration Station. The free-field voltage response and directional patterns in planes containing the cylinder axis (vertical), and planes normal to this axis (horizontal) were obtained. These are shown in Figures 2 to 8, inclusive. The prominent dip in the response at 420 cps, shown in Figure 2, is almost certainly due to the properties of the medium and its boundaries, and appears to be in no way a characteristic of the hydrophone because the frequency at which this dip occurred varied over a frequency range of several hundred cps as the hydrophone and projector (with fixed separation and depth) were moved to different positions in the well.

Except for the prominent dip, the response is essentially flat with a mean value of about -78 db re 1 volt per μbar. One db was added to the measured value to allow for the calculated loss in the cable which had a capacity of about 1275 μμF.

The directivity patterns show that the hydrophone is omnidirectional within ± 1 db in both horizontal and vertical planes over the required frequency range (100 cps to 3 kc). The vertical patterns at 5 and 10 kc are presented merely to show the degree of directionality occurring above 3 kc.

Admittance measurements were made on each of the barium titanate cylinders in air before assembly in order to determine the electromechanical coupling coefficient and the dielectric constant. The measurements were made with the bridge circuit shown in Figure 9 which is simply a doublt admittometer. The variable condenser is first adjusted to produce a null in the reading of V_o at a frequency well below resonance. The setting of this variable condenser gives approximately the clamped admittance (the conductance is quite low). Without changing this setting, the frequency of the signal is now swept through resonance. The reading of V_o is proportional to the motional admittance and its maximum value gives the diameter of the admittance circle. This is given by

$$D_y = \frac{V_o}{10\ V_i} .$$

The Q may be determined from the frequency of maximum motional admittance F_y and the two quadrantal frequencies F_1 and F_2 for which

$$\left| y_{mot} \right| = \frac{D_y}{\sqrt{2}} .$$

The Q is given by

$$Q = \frac{F_y}{F_2 - F_1} .$$

Finally, the electromechanical coupling coefficient is given approximately by

$$k_c = \frac{D_y}{Q\,B_c}$$

where B_c is the clamped susceptance at resonance.

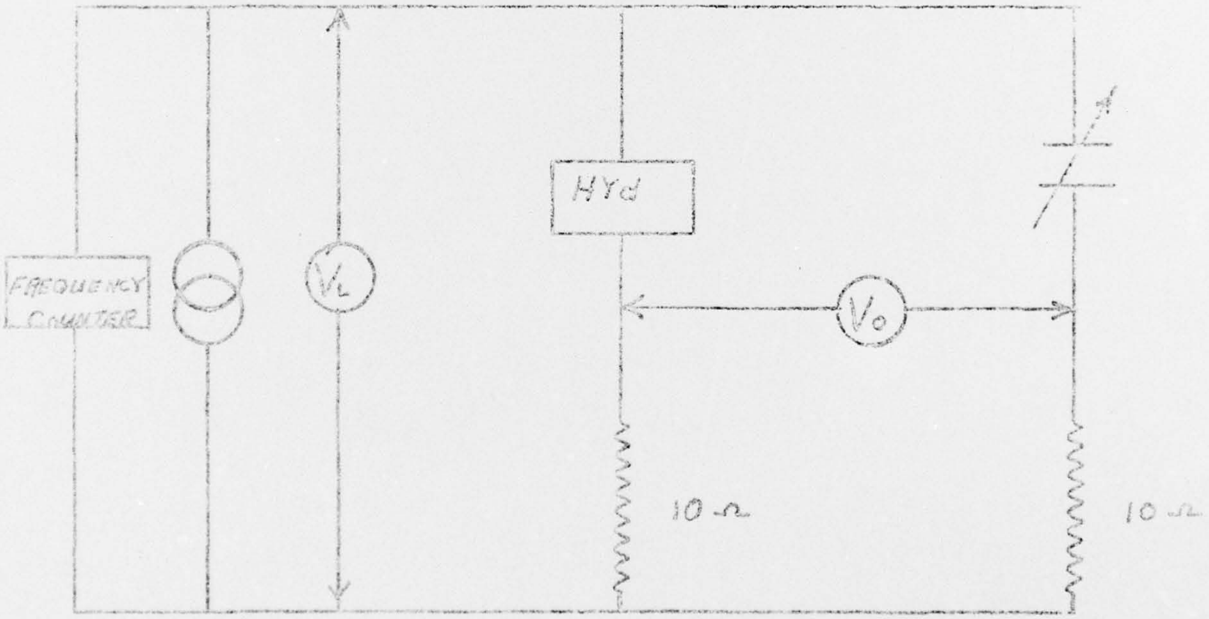

FREQUENCY COUNTER
V_L
HYd
V_o
10 Ω
10 Ω

Figure 9

Bridge Circuit for Measuring Hydrophone Parameters.

The dielectric constant may be computed from the dimensions of the barium titanate cylinder and the measured capacity. Averages obtained from the four elements were used for computing equivalent noise pressure and sensitivity.

These data may now be used to compute the free-field voltage response of the hydrophone which is given by

$$M_o = 300 \sqrt{\frac{4\pi a^2 k_c^2}{E \varepsilon}}$$

where a = radius = 7.63 cm
k_c^2 = (electromechanical coupling coef.)^2 = .0309
E = Young's modulus = 9×10^{11} dynes/cm^2
ε = dielectric constant = 1050 .

The factor 300 converts voltages in e.s.u. to volts.

The expression above gives the sensitivity of a single cylinder and since four of these are connected in series, the hydrophone sensitivity will be four times as much or 20 log 4 db greater. This result turned out to be -74.5 db re 1 volt per μ bar, which compares favorably with the measured value of approximately -78 db re 1 volt per μ bar.

Admittance measurements were also made over the frequency range, 100 cps to 3 kc, using a similar circuit which is shown in Figure 10. A 10,000 ohm standard resistor was placed in shunt with the hydrophone in order to bring the equivalent shunt resistance of the combination down to the values obtainable on the variable resistor now placed in parallel with the variable condenser. When the variable condenser and resistor are adjusted to give a null indication of V_o, their settings are equivalent to that of the hydrophone shunted by the 10 K resistor. From these data, computations of the series resistance were made for use in computing the equivalent noise pressure.

The admittance measurements, especially the conductances, are quite interesting because they show in a very striking manner the relative contributions from the dielectric losses and that due to the acoustic load (motional conductance).

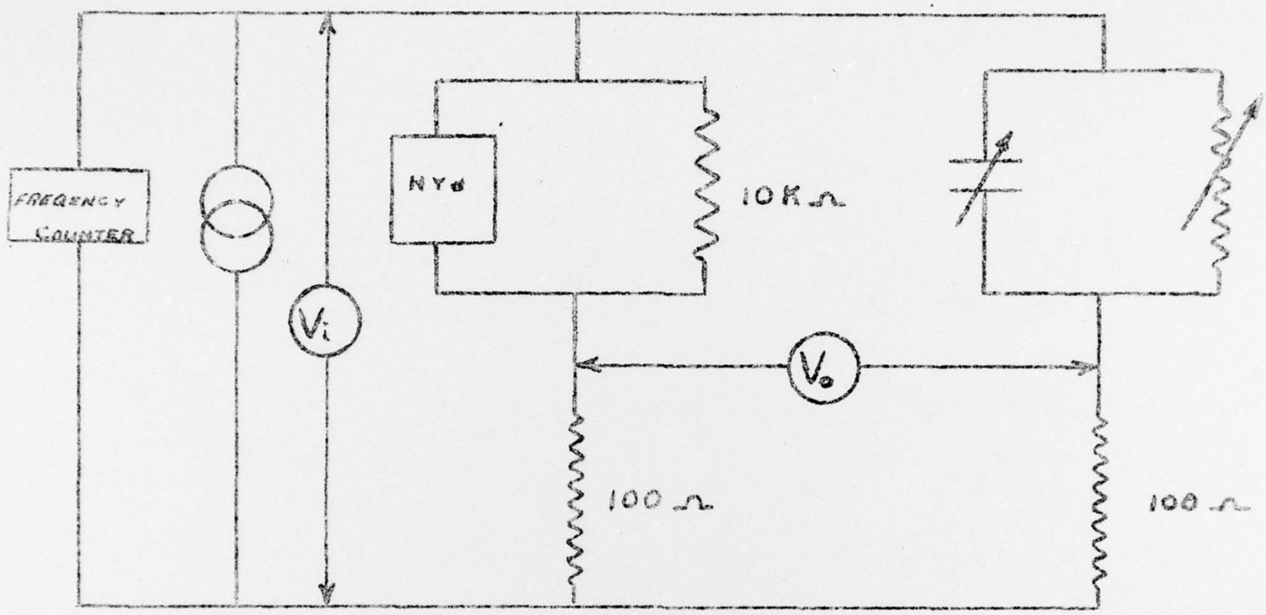


Figure 10

Bridge Circuit for Admittance Measurements.

It is possible to compute the motional conductance from the equivalent circuit shown in Reference 1. The resistance R is given by

$$R = \frac{\rho \omega^2 a^3 \ell}{2 v b E C}$$

where C is the motional capacity. The motional conductance is given by

$$G_{mot} = R \omega^2 C^2 = \frac{\rho \omega^4 a^3 \ell C}{2 v b E} .$$

In computing G_{mot} it is simplest if one first considers the hydrophone as a single cylinder and then, since it actually consists of four similar cylinders connected in series, divide the result by 16 to obtain the motional conductance of the hydrophone.

These computations were made for a range of frequencies covering the range from 100 cps to 3 kc. The results are shown in Table I and in Figure 11.

TABLE I

Frequency cps	Conductance - mhos			
	G_{mot} (calc.)	G_{air}	G_{water}	$G_{mot} + G_{air}$
100	3.36×10^{-12}	$.04 \times 10^{-6}$	$.04 \times 10^{-6}$	$.04 \times 10^{-6}$
250	1.31×10^{-10}	.12	.12	.12
500	2.10×10^{-9}	.24	.26	.24
1000	3.36×10^{-8}	.55	.61	.58
2000	5.37×10^{-7}	1.20	1.66	1.74
3000	2.72×10^{-6}	1.91	3.82	4.63

Since the motional conductance of the hydrophone in air may be neglected, it follows that the values in the last column should be the same as those in the fourth. It is also noted that the motional conductance is quite insignificant at low frequencies but since it varies as the fourth power of the frequency, it actually exceeds the clamped (due to dielectric losses) conductance at 3 kc. These results are also shown in Figure 11.

$$Y = \frac{1}{R + j\omega C}$$

$$\omega = 2\pi f$$

The equivalent noise pressure may be computed from the series resistance which is easily computed from the admittance data. The relation is

$$\text{Eq. Noise Pressure Level} = 10 \log R_{series} - 20 \log M_o - 198.$$

The results are given in Table II.

$$X_C = \frac{1}{\omega C} \qquad Z = \sqrt{R^2 + X_C^2}$$

$$\omega = 2\pi f \qquad Z = \sqrt{R^2 + X_L^2}$$

TABLE II

Frequency cps	Equivalent Noise Pressure Level db re 1 µ bar for a 1 cps band
100	-90.9
250	-94.0
500	-96.8
1000	-96.6
2000	-100.6
3000	-102.0

These values are somewhat lower than expected because the measured value of the loss tangent was less than that generally quoted for barium titanate.

Conclusions and Recommendations

Following is a summary of the most significant hydrophone characteristics, all of which appear to meet the design requirements over the desired frequency range of 100 cps to 3 kc.

1. **Free-field voltage response - Approximately -78 db re 1 volt per µbar over the frequency range of 100 cps to 8 kc.**

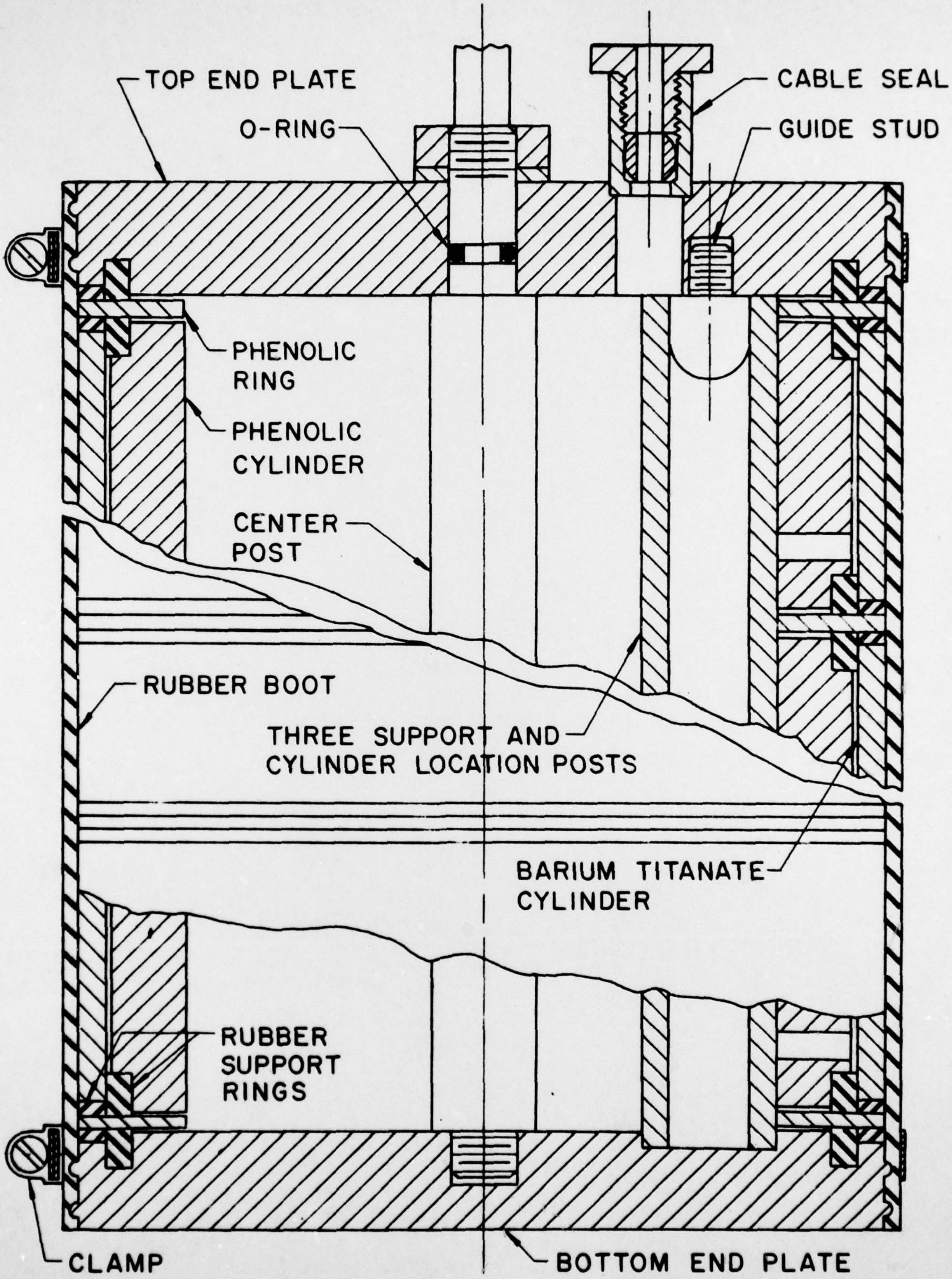
2. Directionality - Omnidirectional within ± 1 db in both horizontal and vertical planes for frequencies up to 3 kc.

3. Equivalent noise pressure level - Varies from -91 to -102 db re 1 μ bar for a 1 cps band from 100 cps to 3 kc, respectively, which is about 52 to 38 db below the ambient noise levels of sea state 0.

4. Hydrophone impedance - The impedance is essentially that due to a capacity of 0.0117 μ farad of which about 0.001 μfarad is due to the cable.

In considering the over-all problem of measuring low level signals, it was learned that the equivalent noise pressure of the amplifier was about 30 db higher than that of the hydrophone when the input to the amplifier simulated that of the hydrophone. This would indicate that the system will just barely measure levels 10 db below zero sea state. There are several things that might have been done, or can be done, to improve this situation. The use of PZT4 with its higher coupling coefficient would increase the sensitivity in the order of 4 db. There are other parameters that would influence this slightly. Since the amplifier can probably handle an impedance about 10 times as great without increasing the noise output, it may be possible to increase the signal-to-noise level by increasing both sensitivity and impedance, which are related. The present barium titanate cylinders could be plated both outside and inside in two or more sections that are separated from each other. Now connecting all these sections in series will increase the impedance and raise the sensitivity. None of these solutions, however, apply to the present hydrophone, but could be incorporated in the next one that is constructed.

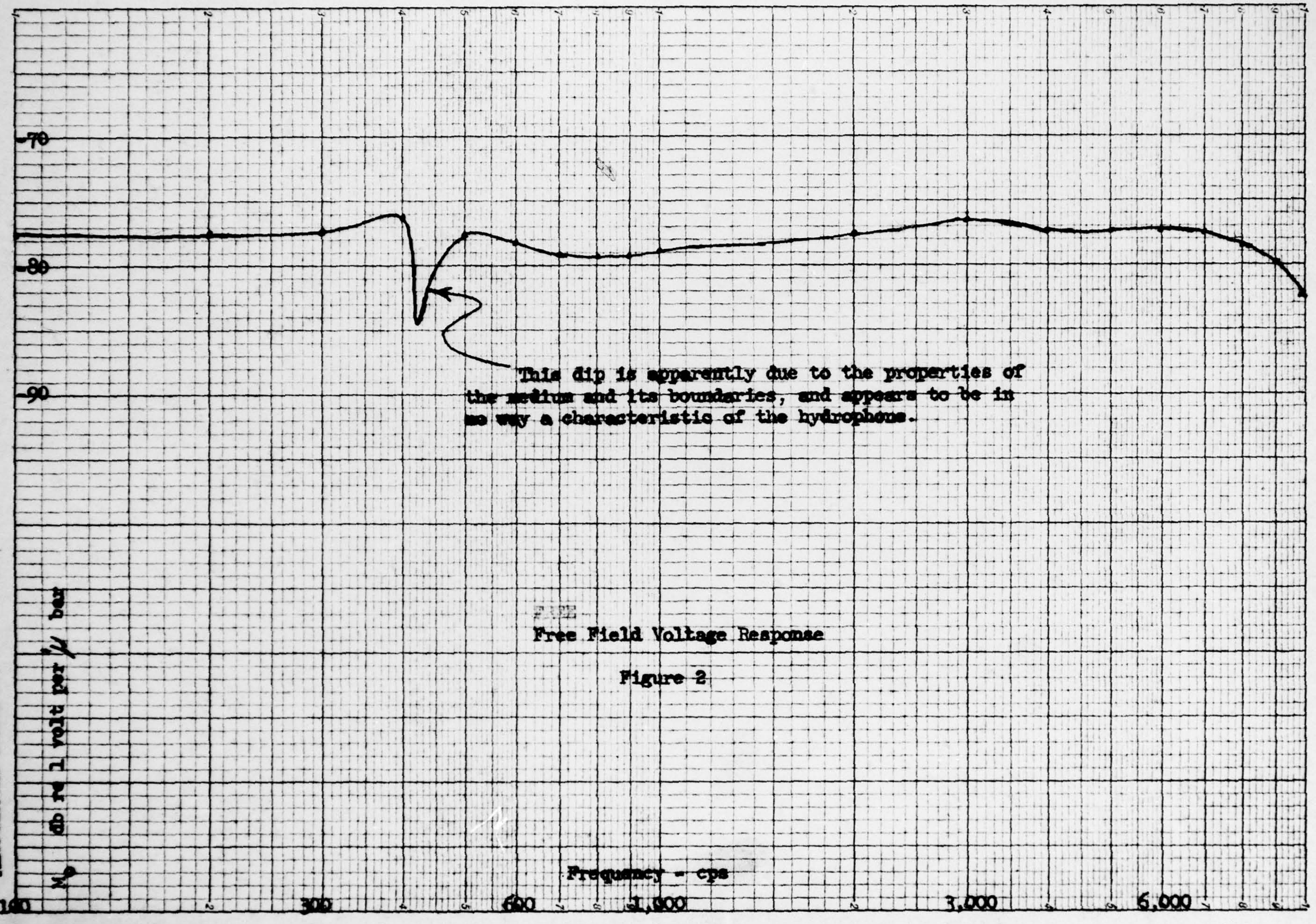
However, there is one possibility for the present hydrophone and that is to feed its output into a transformer with a gain of about 10 db. This would also increase the impedance but that does not necessarily mean that the noise level will be significantly increased.


TOP END PLATE
O-RING
CABLE SEAL
GUIDE STUD
PHENOLIC RING
PHENOLIC CYLINDER
CENTER POST
RUBBER BOOT
THREE SUPPORT AND CYLINDER LOCATION POSTS
BARIUM TITANATE CYLINDER
RUBBER SUPPORT RINGS
CLAMP
BOTTOM END PLATE

Sectional View of Hydrophone

Figure 1

NO. 31,286. 10 DIVISIONS PER INCH (70 DIVISIONS) BY TWO 5-INCH CYCLES RATIO RULING. CODEX BOOK COMPANY, INC. NORWOOD, MASSACHUSETTS. PRINTED IN U.S.A.



This dip is apparently due to the properties of the medium and its boundaries, and appears to be in no way a characteristic of the hydrophone.

Free Field Voltage Response

Figure 2

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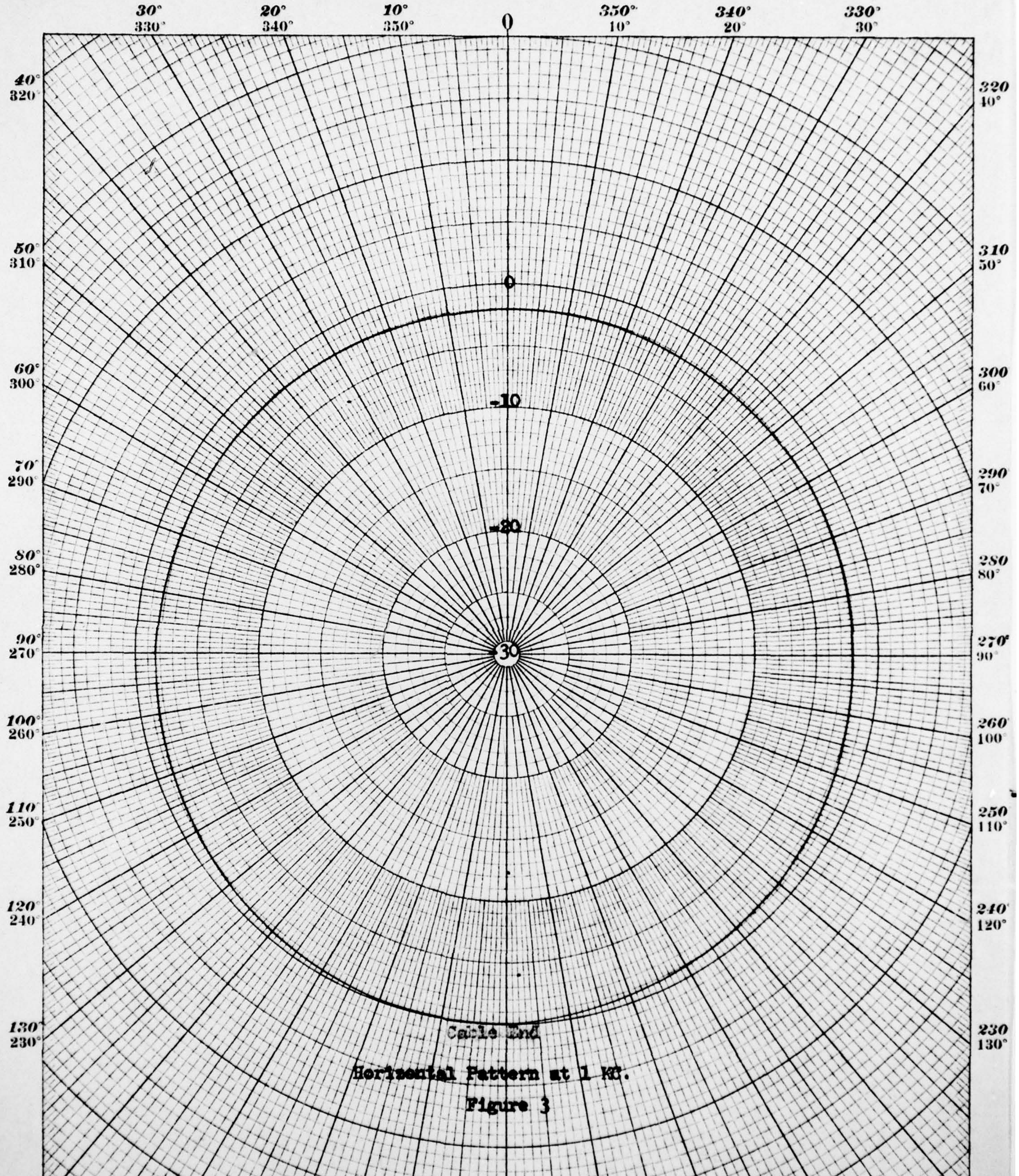

Cable End

Horizontal Pattern at 1 KC.

Figure 3

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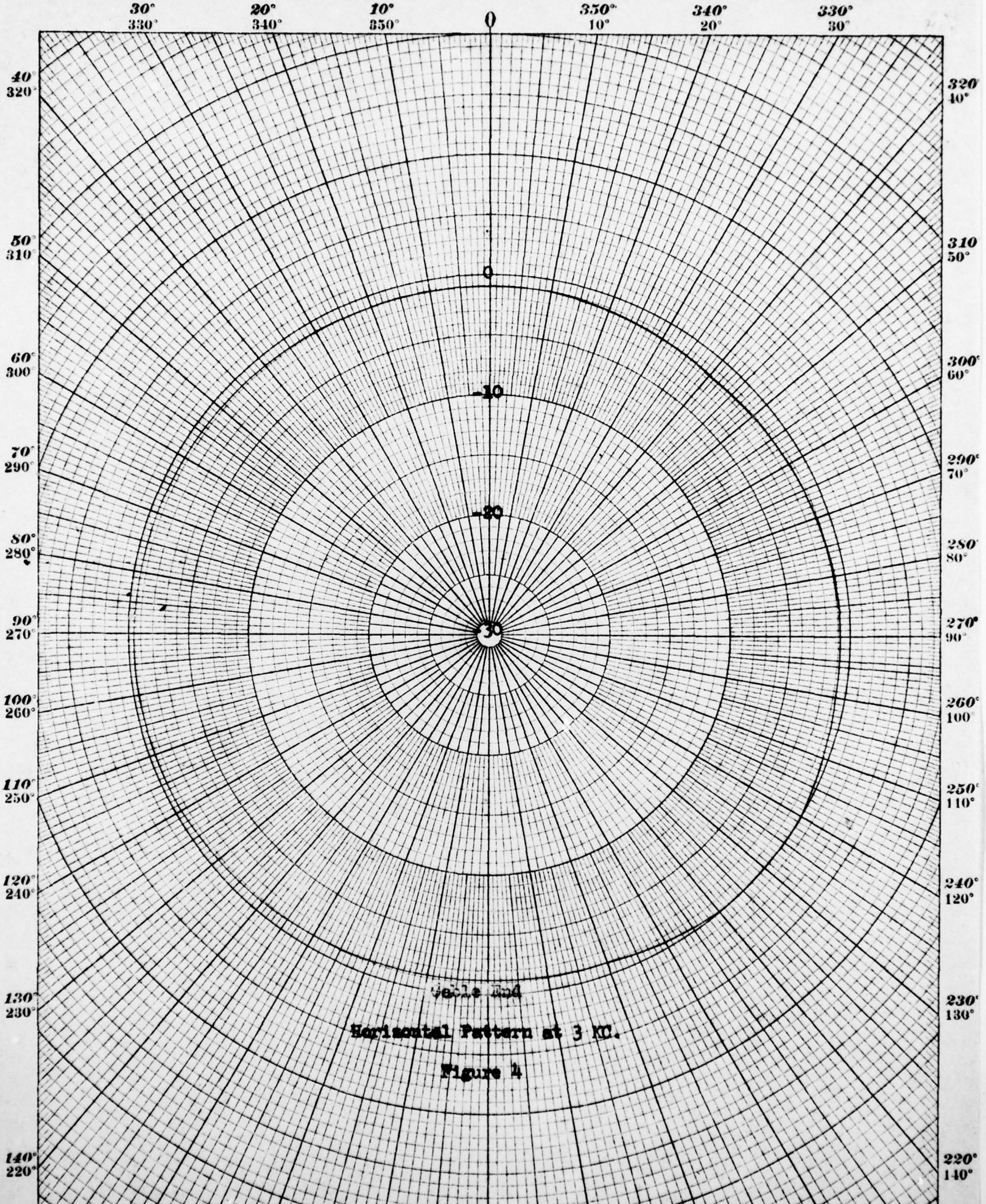

Cable End

Horizontal Pattern at 3 KC.

Figure 4

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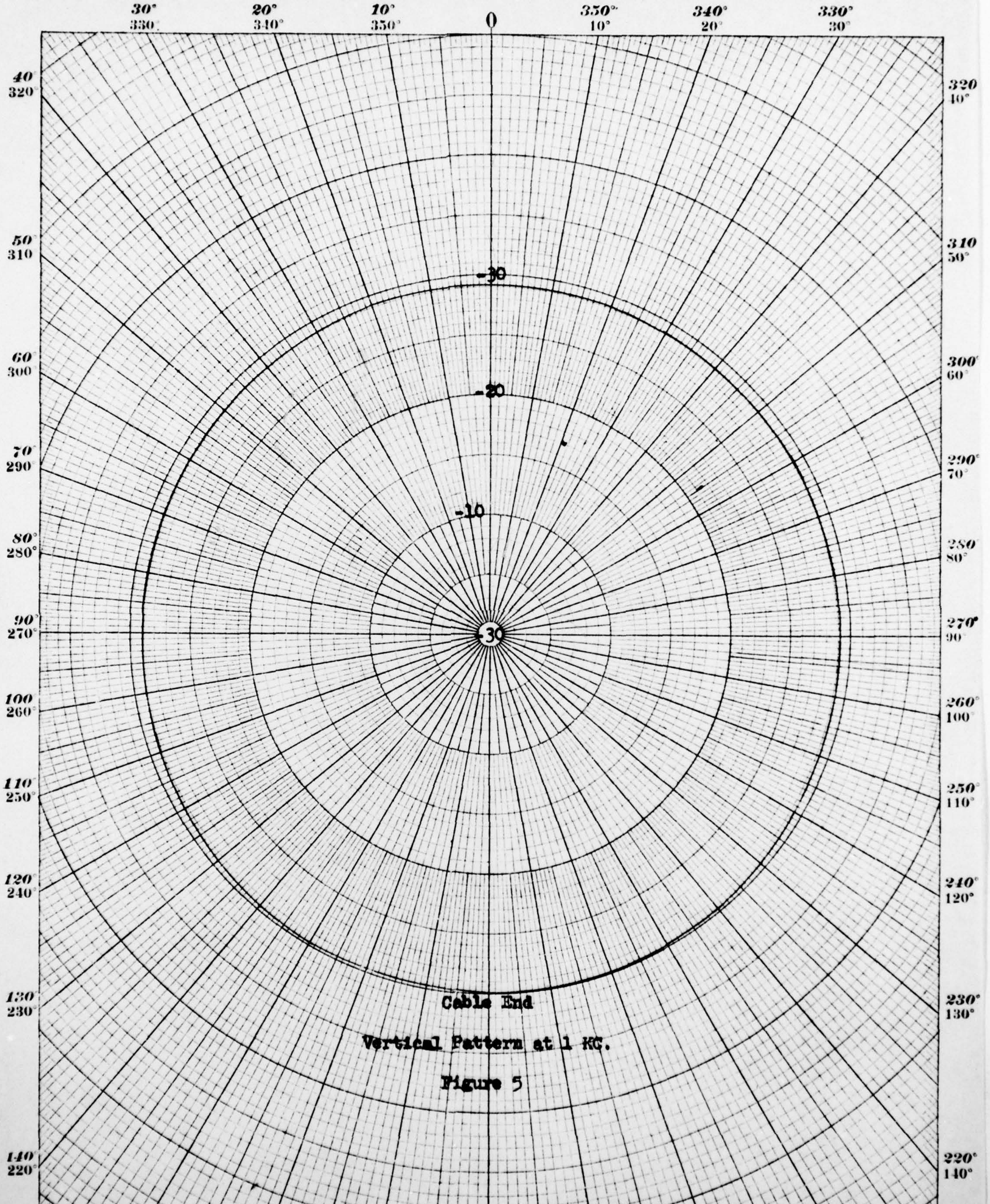
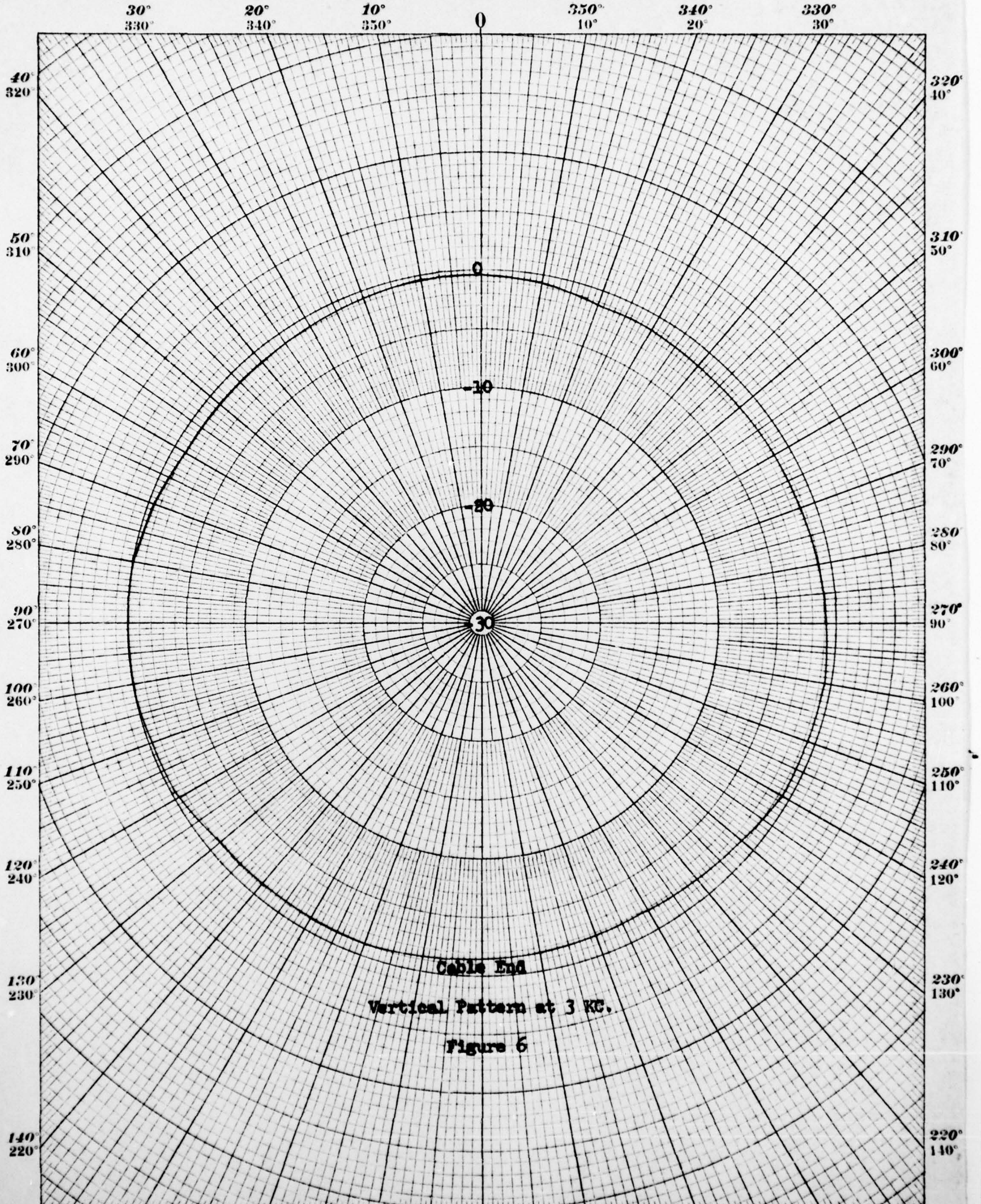


Cable End

Vertical Pattern at 1 KC.

Figure 5



Cable End

Vertical Pattern at 3 KC.

Figure 6

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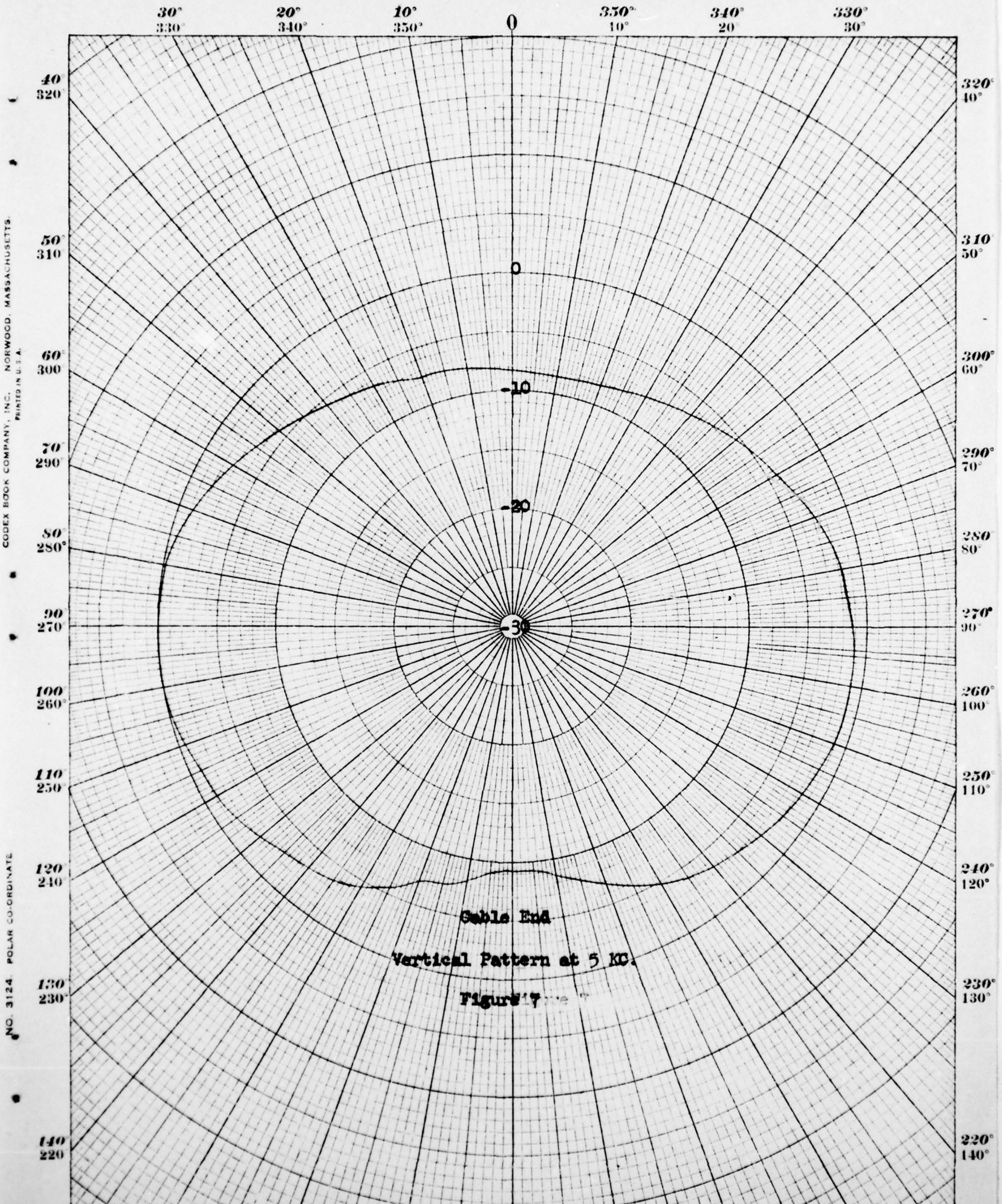

Cable End

Vertical Pattern at 5 KC.

Figure 17

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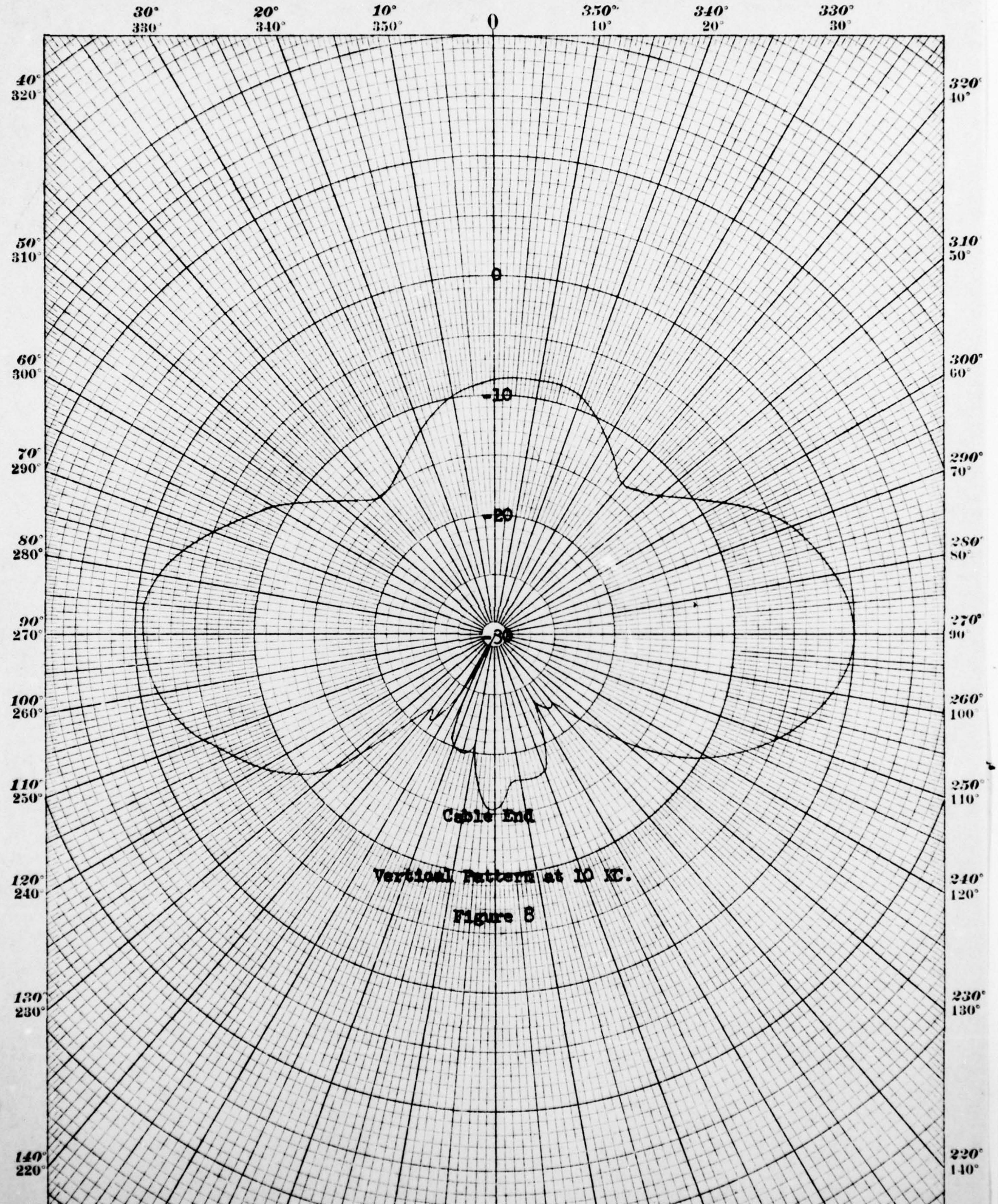
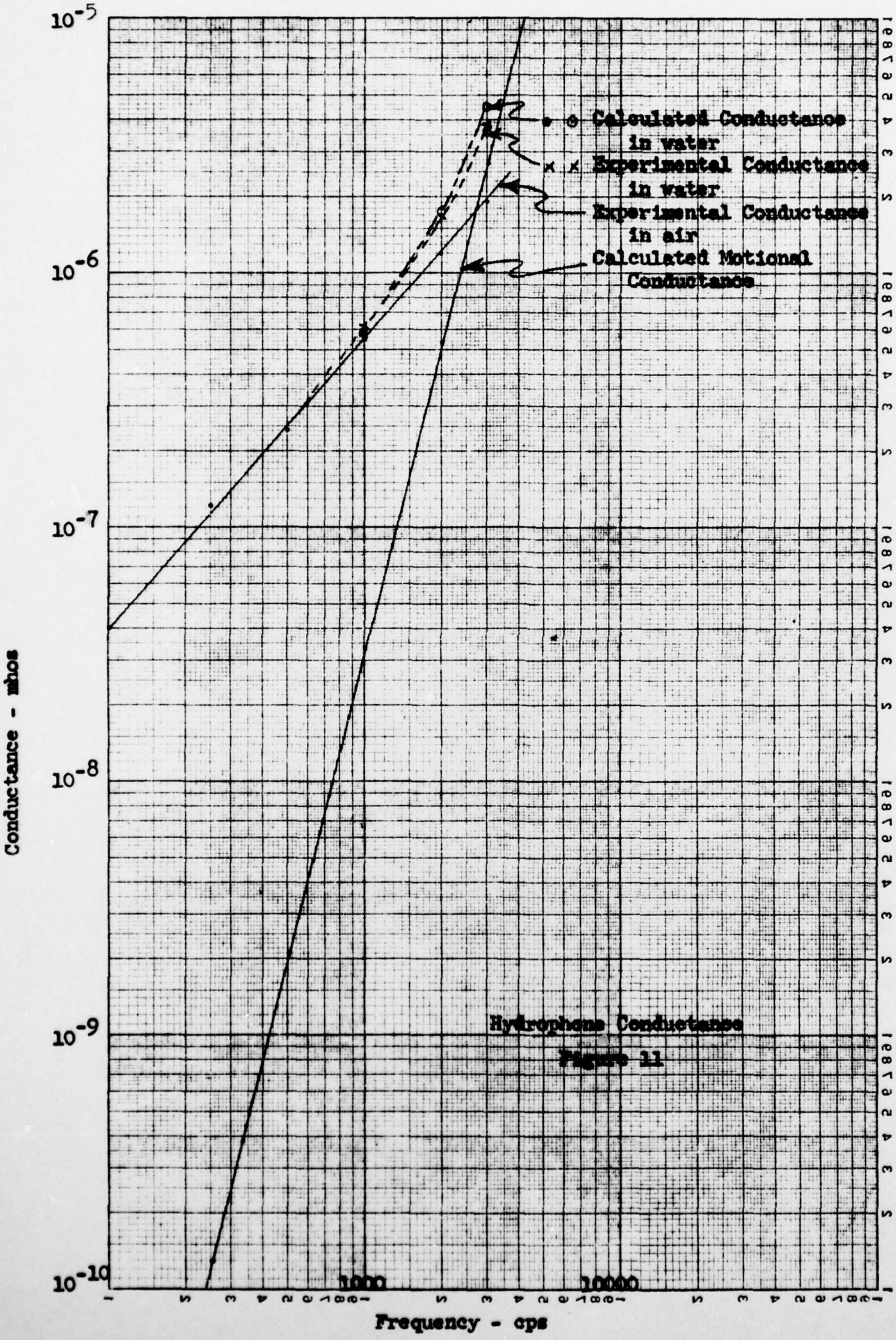


Cable End

Vertical Pattern at 10 KC.

Figure 8



Hydrophone Conductance
Figure 11